

Direct Numerical Simulations of a Temporally Evolving Mixing Layer Subject to Forcing

(NASA-TM-88896) DIRECT NUMERICAL
SIMULATIONS OF A TEMPORALLY EVOLVING MIXING
LAYER SUBJECT TO FORCING (NASA) 22 p
Avail: NTIS HC A02/MF A01 CSCL 20D

N87-23933

H1/34 Unclass
0079516

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Prepared for the
10th Symposium on Turbulence
cosponsored by the Office of Naval Research
and the University of Missouri—Rolla
Rolla, Missouri, September 22-24, 1986



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Abstract

The vortical evolution of mixing layers subject to various types of forcing is numerically simulated using pseudospectral methods. The effect of harmonic forcing and random noise in the initial conditions is examined with some results compared to experimental data. Spanwise forcing is found to enhance streamwise vorticity in a nonlinear process leading to a slow, secondary growth of the shear layer. The effect of forcing on a chemical reaction is favorably compared with experimental data at low Reynolds numbers. Combining harmonic and subharmonic forcing is shown to both augment and later destroy streamwise vorticity.

Nomenclature

Y_0 = radial location where $U = (U_{-\infty} + U_{+\infty})/2$

λ = forcing wavelength

$\theta_{0.90}$ = radial distance where the flow reaches 90 percent of U_{∞}

Introduction

Direct numerical simulations of turbulent flows are increasingly being used to extract turbulent flow physics (e.g., refs. 1 and 2). This technique has distinct advantages over laboratory experiments. First, numerical simulations can unambiguously perform experiments where the effect of changing one single parameter can be individually studied in detail. Experimental studies, done in the laboratory, can rarely separate individual cause and effect trends. Second, numerical simulations contain all the information concerning flow dynamics. Various statistical properties can be easily extracted from the computations. Laboratory experiments usually cannot measure all important flow quantities and measurement accuracy is always a problem.

But numerical simulations are not without basic limitations as well. Although numerical simulations can sample any statistical quantity, these computations are very computer intensive, requiring on the order of several CPU hours to calculate only a few seconds of flow time. Whereas an experiment can usually be run for hours to measure various statistics, the numerical simulations have to be sampled over a much shorter time period. Another limitation of the numerical simulations is related to the range of turbulent scales which can be represented on the computational mesh. In direct numerical simulations, highly accurate (pseudospectral) numerical methods are used to solve the Navier-Stokes equations on a computational mesh. Despite the high phase and amplitude accuracy of these techniques, turbulent fluctuations both larger than

and smaller than the computational mesh cannot be resolved. The later restriction limits the simulation to a low Reynolds number flow (approximately 50 to 100 based on the Taylor microscale). When one applies the results of a low Reynolds number calculation to understand high Reynolds number turbulence, an inherent assumption is made that the large energetic scales of turbulent motion display characteristics that are Reynolds number independent. Testing of this assumption provides part of the motivation for this report.

Another motivation for this report is to examine the impact of vortical motion on mixing and chemical reactions in a planar mixing layer. The planar mixing layer is a convectively unstable type of flow in which small perturbations, either naturally occurring or induced by the flow hardware, can rapidly grow as these perturbations are convected downstream (ref. 3). This prototypical flow provides a unique opportunity to study the effect of small changes in the initial conditions of the flow and to observe how these changes alter the characteristics of a passive chemical reaction. A chemical reaction is quite sensitive to the dynamics of mixing at the smallest scales (ref. 4), and this will be examined in a comparison with experimental data.

There have been a number of previous numerical studies of mixing layers (refs. 5 thru 8). In relation to this report, the most pertinent of these is reference 5, in which the importance of large scale motions in enhancing chemical reactions is illustrated. Primarily, this study used two-dimensional numerical simulations to represent the increased interfacial area and enhanced entrainment that can result from large scale vortex rollup. However, two-dimensional simulations cannot represent the small-scale (inherently three-dimensional) structures that have been experimentally shown to occur in the mixing layer. These small-scale structures lead to a substantial increase in scalar mixing (ref. 9). The formation of these structures and the related increase in mixing is termed the "mixing transition." Before the mixing transition the flow is principally two-dimensional and laminar. After the mixing transition the flow is turbulent and three-dimensional while still retaining some of the characteristics of two-dimensionality. Previous studies have failed to observe the onset of the mixing transition because of a lack of grid refinement limiting the resolvable Reynolds number. The mixing transition occurs somewhere around a Reynolds number of 5000 (based on the local momentum thickness), whereas the simulations are typically one-fifth this level.

A new generation of supercomputers is currently becoming available which should eliminate this restriction. The first high speed processor obtained under NASA's Numerical Aerodynamic Simulation (NAS) project combines a relatively fast CPU with about 258 million words of memory. This may permit numerical simulations up to and perhaps beyond the mixing transition. This report details the initial calculations made with the NAS in a continuing study to examine various factors influencing mixing in chemically reacting, mixing layers. The effects of various types of forcing are studied and the vortical evolution of the flow is graphically illustrated. Although these calculations were made typically at low Reynolds number, they form the basis for future high Reynolds number studies.

Computational Approach

The numerically-simulated mixing layer is conceptually represented as shown in figure 1. The orientation of typical streamwise and spanwise vorticity along with the orientation of the axes is illustrated. The mean axial velocity profile is initially set to a hyperbolic-tangent profile representative of experimental data (ref. 10). Imposed on this profile is a low level of random noise corresponding to a noise spectrum that is well resolved on the computational mesh. This provides a divergence-free, low level (typically less than one percent) of turbulence in all velocity components. To simulate spanwise forcing, harmonic and (sometimes) subharmonic perturbations are imposed in the initial conditions to generate a rapid spanwise-vortex rollup.

The time-dependent Navier-Stokes equations are solved for incompressible flow. Three scalar transport equations are solved to simulate a passive (no heat release) chemical reaction. This system of differential equations is solved explicitly by using second-order accurate time-differencing and pseudospectral approximations (Fourier series) of the spatial field as noted in reference 6. Spherical wavenumber truncation was performed by following the method described in reference 11. The flow Reynolds number was about 200 based on the initial velocity thickness, and the Damkohler number of the chemical reaction was set to 5.

The computational box size for these numerical simulations was scaled to include one complete cycle of the longest forced wavelength in the X (axial) direction. The Y direction was typically slightly more than twice this length, and the Z direction extent was typically equal to one-half the X direction length. Grid points were equally spaced along each direction. Boundary conditions in the X and Z direction were periodic. In the Y direction, no stress type boundary conditions were used; quantities such as U (axial velocity) were set to provide a zero gradient across the boundary and quantities such as V (radial velocity) were set to provide a reflection across the boundary.

As noted previously the numerical simulations reported here are for a time-evolving mixing layer. This comprises a Lagrangian description of the spatially developing mixing layer with the computational domain following the mean flow velocity. The drawback that this imposes in comparisons with experimental data is offset by the increased numerical resolution available in the Lagrangian description of the flow. The time-evolving simulation cannot represent some important features of experimental data (such as the asymmetric development of the layer) and should be looked at as more of a tool to study "idealizations" of real flows where the primary aim is to study the structure of turbulent flows.

Results and Discussion

Numerical simulations of mixing layers subject to various types of forcing are examined here. Initially, the effect of harmonic forcing and random noise in the initial conditions is examined and some results are compared with experimental data (refs. 12-13). In the second section, the effect of combined harmonic and subharmonic forcing is illustrated. The wavelength of the harmonic forcing corresponds to the most amplified

frequency as predicted from linear stability theory (ref. 10). The subharmonic is twice this length.

Harmonic Forcing and Random Noise

A series of numerical simulations of a mixing layer subject to harmonic forcing is compared to the experimental data of references 12 and 13. Both of these experiments employed a high degree of spanwise forcing in the entrance flow. This simplifies the specification of the initial conditions for the numerical simulation, since the high level of spanwise forcing dominates the natural random noise normally associated with high Reynolds number experimental flows. The spatially evolving shear layer is among those types of flows classified as convectively unstable; therefore, any small disturbance can rapidly grow as it is convected downstream. The highly excited harmonic forcing should grow more rapidly than the lower level random disturbances. This leads to the early part of the flow being largely two-dimensional. By taking advantage of this fact, we will examine how well a two-dimensional numerical simulation describes the velocity field of a harmonically excited shear layer.

The mean velocity half-width calculated from a two-dimensional numerical simulation (64x65 grid points) with harmonic excitation is compared to the experimental data of reference 12 in figure 2. For this comparison, data from the slow speed side of the layer is chosen as the dynamics of growth and saturation are more apparent than on the high speed side. It should be noted that the simulation is of a time-evolving layer whereas, the experiment spatially evolves, a transformation similar to that described in reference 8 must be performed to relate the spatial and temporal information. Once this transformation is performed the evolution of the experimental data is well simulated up to the point of saturation of the shear layer (60-80 cm). Beyond this point (> 100 cm) the slow growth of the layer is simulated poorly. Enlarging the computational domain and inputting various perturbations fails to reproduce the slow growth represented in the experimental data. The two-dimensional simulations simply exhibit vortex nutation or a change in the orientation of the axis of the rolled-up vortex with no significant increase in shear layer width. These results are similar to the findings of reference 14 where two-dimensional simulations were compared to the experimental data of Ho and Huang (ref. 15). Again the simulations fairly represented the early rollup and saturation, but failed downstream of this region. Reference 16 indicates that streamwise vorticity can be more significant beyond saturation, and these results tend to support that finding. In other words, the two-dimensional simulations fail to represent the growth of three-dimensional streamwise vorticity following saturation in the shear layer.

The Reynolds stresses at two different axial locations are compared in figure 3. The locations selected for comparison are within the region where the flow is primarily two-dimensional; hence, the comparison between simulation and experimental data is qualitatively good. The simulation does not match the peak experimental values, and the simulated profiles appear to be spread over a greater radial distance than the experimental data; however, the change in sign observed experimentally is faithfully reproduced. This correctly represents the change in the energy transfer between the

mean flow and the turbulence. When the Reynolds stresses are negative, energy is transferred from the turbulence to the mean flow causing the decrease in shear layer thickness seen in figure 2 (around 60 cm). The failure of the simulation to more closely match the experimental data profile is probably due to the difference in Reynolds number between the two flows.

The mean velocity half-width of three-dimensional simulations (32x33x32 grid points) using harmonic forcing with a low level of random noise or just random noise with no forcing is displayed in figure 4. The simulation using harmonic forcing exhibits a development similar to the two-dimensional calculations (figure 2) up to and just beyond the point of saturation. Beyond saturation the three-dimensional forced simulation displays a slow, steady growth which is in general agreement with the experimental trend. In contrast to the forced results, the mean velocity half-width of the "random noise only" simulation indicates a much slower overall growth of the shear layer.

Three-dimensional surface plots of constant vorticity are shown for the harmonic forcing simulation in figure 5. In the streamwise vorticity plots, both positive and negative vorticity levels are displayed with alternate colors indicating the change in vorticity rotation. The streamwise vorticity is weak and poorly organized at $T=19.2$ seconds, whereas, counter-rotating vortex pairs are clearly evident in the $T=43.2$ seconds plot. These are the mushroom-shaped structures experimentally observed by Bernal (ref. 17). In the simulation these structures evolve from the weak level of random noise included in the initial conditions. It is interesting to note that these structures do not get organized until after saturation of the harmonic wave. Apparently the orientation of the main spanwise vortex, which is involved in the change in sign of the Reynolds stresses (ref. 18) also contributes to the generation of streamwise vorticity.

Total vorticity surface plots are also shown in figure 5 for $T=19.2$ and 43.2 seconds. Two different magnitudes of vorticity are color coded to indicate that the strongest vorticity is associated with the harmonic rollup (or spanwise vorticity). A lower level of total vorticity is also plotted to display the formation of streamwise vorticity on the spanwise structure. At much later times the spanwise vorticity grows sufficiently in strength to disrupt the spanwise structure.

Figure 6 displays the results of a high resolution calculation of the harmonically excited shear layer. In this simulation, 128x129x32 grid points are used to more fully resolve the flow field. Essentially, the dynamics of the flow are unchanged from the results noted earlier indicating that the vorticity field is sufficiently well resolved in these simulations. Also evident in the simulation is the distortion of the spanwise structure caused by the strong streamwise vorticity. The streamwise vorticity appears to gain energy at the expense of the spanwise structure.

Three-dimensional surface plots of constant vorticity for the numerical simulation with random noise only in the initial conditions are shown in figure 7. From these images it is apparent that both the spanwise structure and the streamwise vorticity take longer to evolve. Although the spanwise structure takes longer to evolve, the streamwise vorticity again does not appear until after saturation of the harmonic wave. Once it does form, the streamwise vorticity is notably weaker than the streamwise

vorticity that formed under harmonic forcing (fig. 5). Despite the fact that harmonic forcing adds no energy into the Z direction modes, the nonlinear interaction with the spanwise structure is important to the formation of the streamwise vorticity.

Forcing can also have a notable impact on scalar mixing and, thereby, on a chemical reaction. The previous two numerical simulations were repeated using much finer mesh resolution (128x129x32 in the X, Y, and Z direction respectively) to accurately simulate a passive chemical reaction. Figure 8 displays the results of these calculations compared with the experimental data of reference 13. (Here the total product versus time from the simulations is compared to the experimentally measured product thickness as defined in ref. 13. This provides a qualitatively comparable basis for examining both flows.) The effect of experimental forcing noted at low Reynolds number is qualitatively similar to the trend seen in the numerical simulations. Since the numerical simulations are for a low Reynolds number (less than 1000 based on the local momentum thickness) this qualitative agreement is expected. What seems unusual about these results is that the effect of increased mixing that should result from the formation of strong streamwise vorticity (especially in the forced simulations for times greater than 20 seconds) is not readily apparent. Purely two-dimensional simulations (with no streamwise vorticity) display very similar levels of product formation. Previous simulations have shown that the majority of the product is formed in the vortex cores (ref. 5). The braid region contributes only slightly to the total amount of product formed. Therefore, though the streamwise vorticity may increase product formation, it only does this along the braids, and does not significantly affect the total amount of product formed.

In the high Reynolds number experiment, the rapid increase in product formed for distances greater than 20 cm may be due to increased mixing resulting from smaller scale streamwise vorticity. Numerical simulations (not shown) run at a higher Reynolds number, but with no other changes in the simulation, actually produced less product than the low Reynolds number simulation primarily because of the reduction in diffusivity necessary to maintain a constant Prandtl number. This is certainly contrary to the experimental trend. It seems likely that as the Reynolds number is increased in these simulations, the initial noise spectrum will also have to be changed to add more energy at the higher wavenumbers. This would more closely replicate "real" experimental flows which have more small-scale fluctuations at the high Reynolds number. These additional small-scale fluctuations might make up for the reduced diffusivity and lead to greater product formation.

Combined Harmonic and Subharmonic Forcing

The temporal evolution of both streamwise and total vorticity of a shear layer subject to harmonic and subharmonic forcing is displayed in figures 9, 10, and 11. At a time of 15 seconds (fig. 9), fairly coherent counter-rotating pairs of streamwise vorticity are apparent in the region between the two spanwise vorticities. Less well organized streamwise vorticity is obvious in the braid region at the limits of the X axis, resulting from the strong random noise in the initial conditions. At a time of 24 seconds (fig. 10), the two forced spanwise structures are merged together. This merging greatly reduces the area between the two structures and vortex stretching

enhances the streamwise vorticity in this region. This streamwise vorticity is rotated approximately 270 degrees between $T=15$ and 24 seconds, whereas, the streamwise vorticity in the outer braid region is stretched to a much lesser extent. At $T=33$ seconds the streamwise vorticity in the center of the new merged vortex core is no longer apparent in the simulation. Dissipation being proportional to the square of the vorticity, it appears that these streamwise structures are so strongly stretched that they become sensitive to the viscosity of the fluid. There exists no strong mechanism (such as a mean shear in the proper direction) to transfer energy into these structures as rapidly as it is dissipated, therefore, the vorticity in the vortex core disappears. The Reynolds number of this flow remains less than 1000 during the calculation so that the dissipation that occurs in this simulation may not occur in high Reynolds number flows. This Reynolds number effect can be a significant factor in the transition to turbulence process. As the viscosity of the fluid is reduced (as the Reynolds number increases) these small intense streamwise structures should play an increasingly more important role in turbulent mixing. The large (forced) spanwise structures will entrain fluid which will then be intensely mixed by the remnants of the streamwise vorticities as suggested by reference 19.

The subharmonic pairing process is also evident in the high resolution simulations of figure 12. In these figures the total vorticity is used to simultaneously observe both the streamwise vorticity and the forced spanwise structures. These calculations used $128 \times 129 \times 32$ grid points to resolve the flow field and the random noise was introduced at a very low level (<0.1 percent). This lower level of random noise leads to the development of much less streamwise vorticity which is readily dissipated by vortex stretching. Some streamwise vorticity is apparent at $T=9$ seconds in the braid region, but no streamwise vorticity is evident between the large spanwise structures as they collide ($T=18$) and merge ($T=27$). At $T=36$ seconds some streamwise vorticity appears to regenerate based on the rollup of the single merged vortex.

The evolution of streamwise vorticity in this flow suggests an answer to the rescaling question posed in reference 20. Experimentally it has been observed that the streamwise vorticity appears to rescale after the pairing process with fewer streamwise vortex pairs evident after pairing of the spanwise vortices. These simulations suggest that the streamwise vorticity is regenerated based on the local scale of the spanwise structure. Of course, these simulations cannot provide a definitive answer because of the limits on Reynolds number in the simulated flow, and the dissipating effect this has on the small-scale streamwise vorticity. In addition, attempting to draw definitive conclusions based on only one numerical simulation is analogous to using a single flow visualization experiment which may or may not be representative of the usual behaviour of the flow. Additional simulations are necessary to build up confidence in the noted results.

Summary of Results

Numerical studies of a planar mixing layer subject to various types of forcing indicate

1. Low Reynolds number direct numerical simulations qualitatively represent some velocity field features of a high Reynolds number turbulent shear layer subject to harmonic forcing.

2. The effect of forcing on a chemical reaction is qualitatively similar for low Reynolds number experimental data and numerical simulations. Currently, the experimental trends seen at high Reynolds number have not been accurately simulated.

3. Streamwise vorticity is greatly enhanced by periodic spanwise forcing and can contribute (albeit weakly) to shear layer growth.

4. In low Reynolds number numerical simulations of the vortex pairing process, streamwise vorticity can be both significantly enhanced and then dissipated as the spanwise vortices merge.

Concluding Remarks

The active control of turbulence through various types of forcing has a great potential for manipulating combustion processes. The numerical simulations displayed in this report have indicated some of the changes in vortical structure that are possible using various types of forcing. Although current simulations of chemical reactions have only compared favorably with low Reynolds number data, it seems likely that the high resolution computations, that are now possible, will overcome this limitation. The resulting increased understanding of chemically reacting flows that will evolve from these studies promises significant technological benefits for many applications.

Acknowledgements

The author is pleased to acknowledge many useful discussions with R.W. Metcalfe (Flow Research), J.J. Riley (University of Washington), P. McMurthry (University of Washington) and G. Mungal (Stanford University). This research was performed while the author was working at the Ames Research Center and the assistance of several individuals there is gratefully acknowledged.

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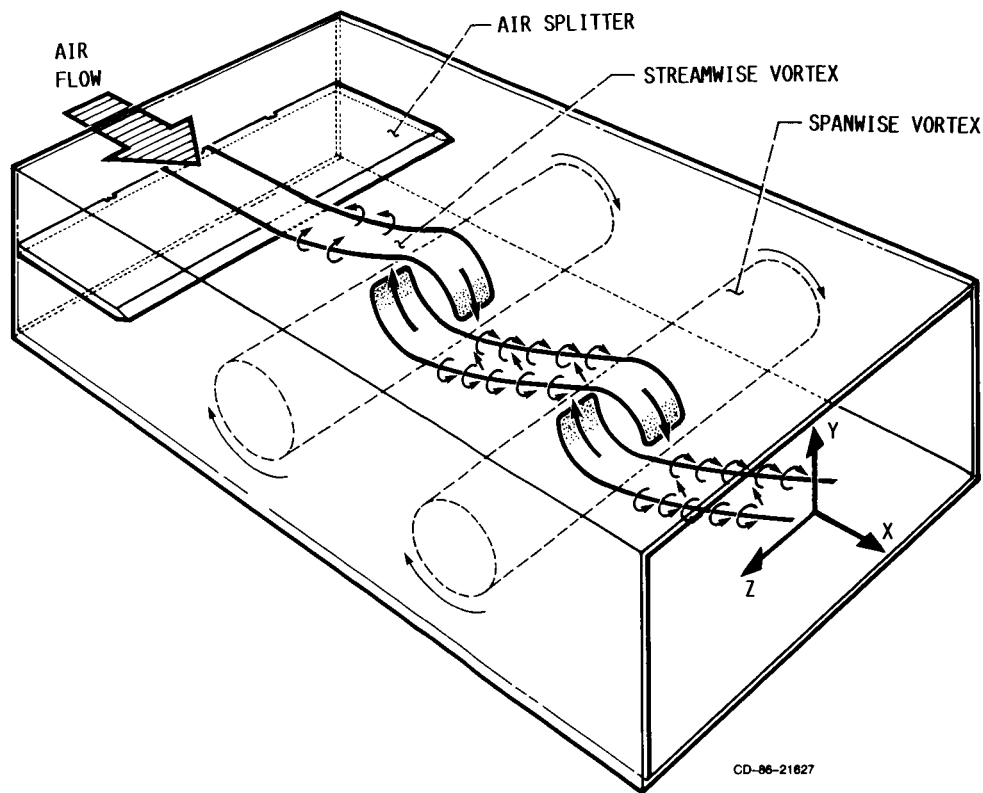


FIGURE 1. - SCHEMATIC REPRESENTATION OF THREE-DIMENSIONAL, PLANE SHEAR LAYER.

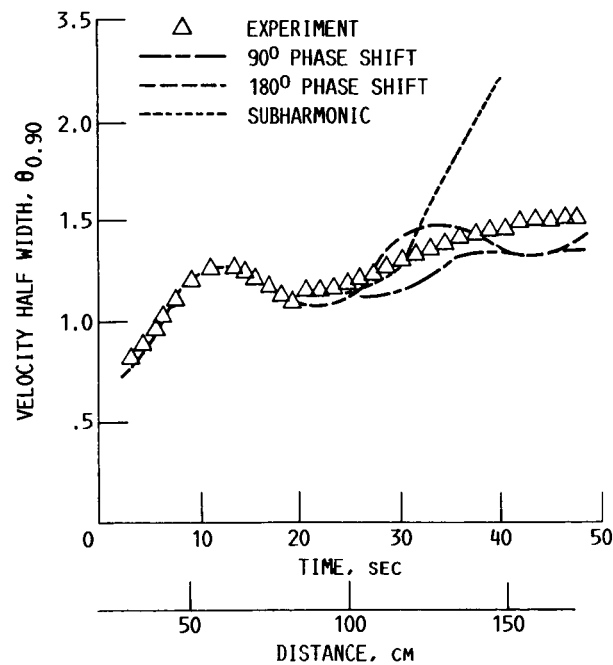


FIGURE 2. - EVOLUTION OF MEAN VELOCITY HALF-WIDTH AS FUNCTION OF TIME (FOR NUMERICAL SIMULATION) AND DISTANCE DOWNSTREAM (FOR EXPERIMENT). AT $T = 24$ SECONDS AN ADDITIONAL PERTURBATION WAS ADDED TO SIMULATION AS NOTED.

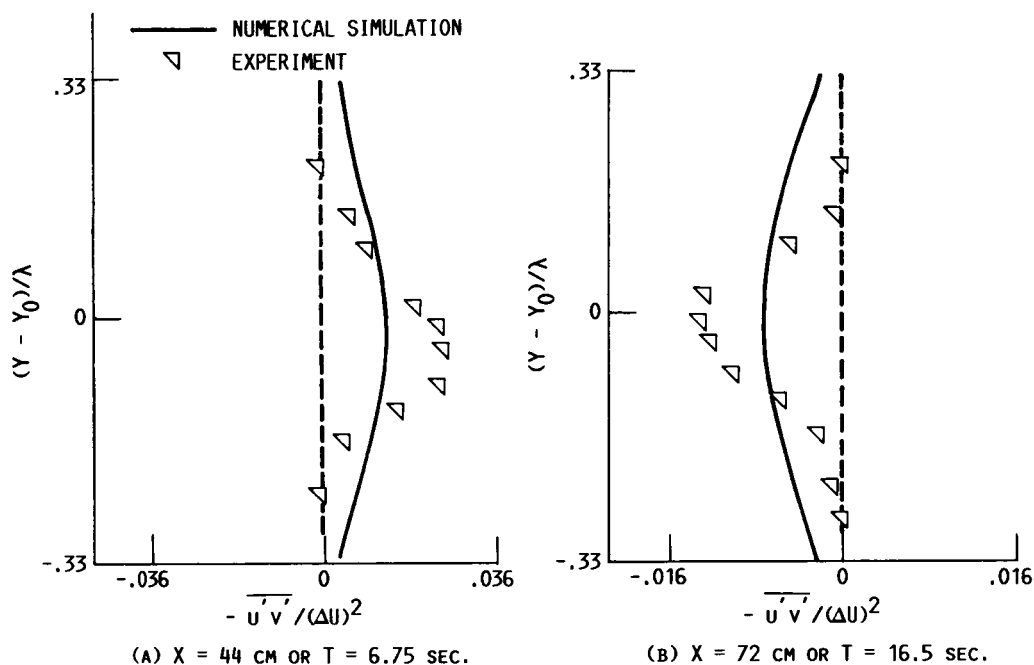


FIGURE 3.- REYNOLDS SHEAR STRESSES IN CONSTANT DENSITY SHEAR LAYER: COMPARISON BETWEEN TWO-DIMENSIONAL NUMERICAL SIMULATION AND EXPERIMENTAL DATA, REFERENCE 12.

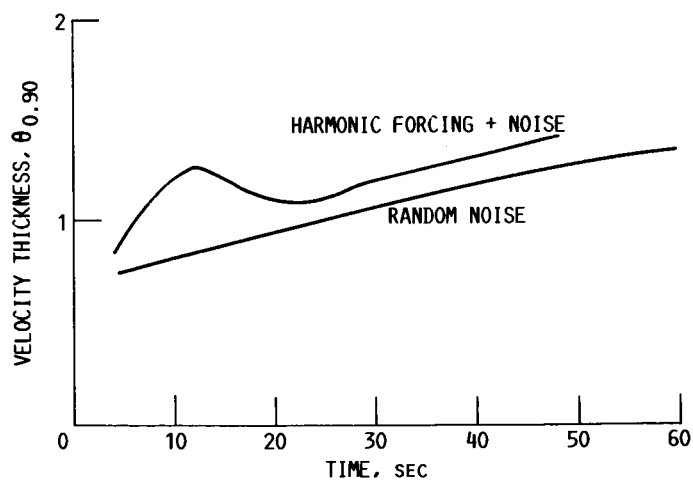


FIGURE 4. - EVOLUTION OF MEAN VELOCITY HALF-WIDTH FOR THREE-DIMENSIONAL NUMERICAL SIMULATIONS WITH AND WITHOUT HARMONIC FORCING.

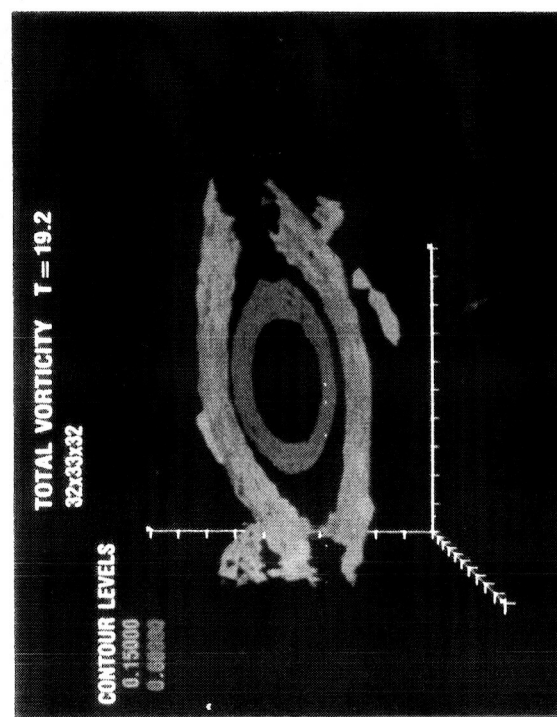
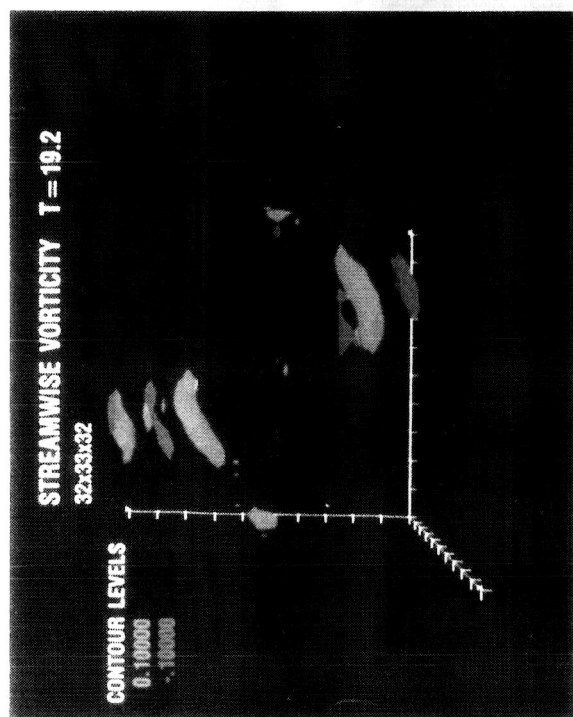
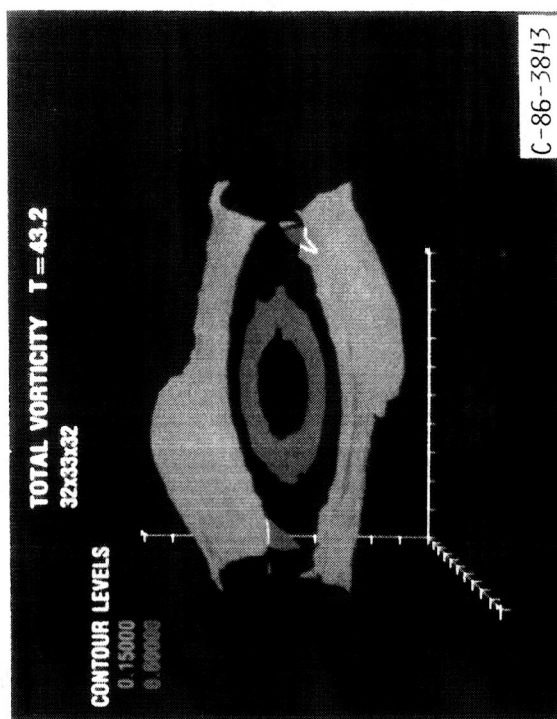
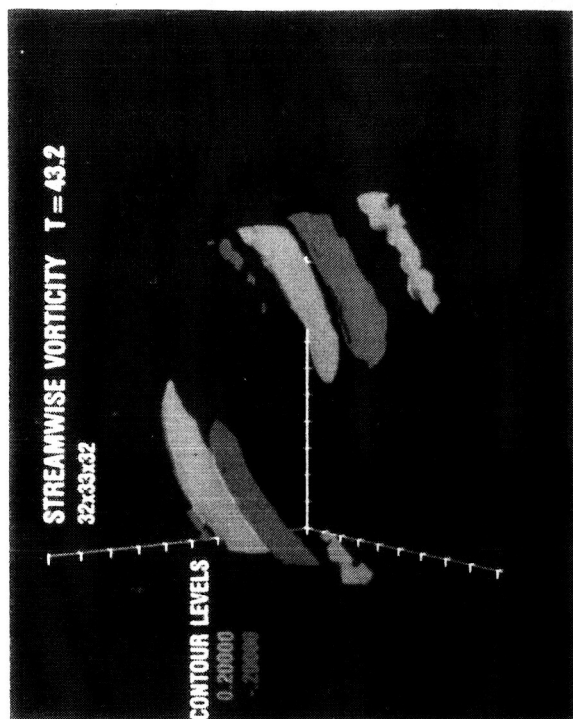


FIGURE 5. - THREE-DIMENSIONAL SURFACE PLOTS OF CONSTANT (STREAMWISE OR TOTAL) VORTICITY FOR HARMONICALLY EXCITED MIXING LAYER. CONTOURS ARE SHOWN FOR TWO DIFFERENT TIMES, $T = 19.2$ AND 43.2 SECONDS. $32 \times 33 \times 32$ GRID POINTS ARE USED IN THE X, Y, AND Z DIRECTION, RESPECTIVELY.

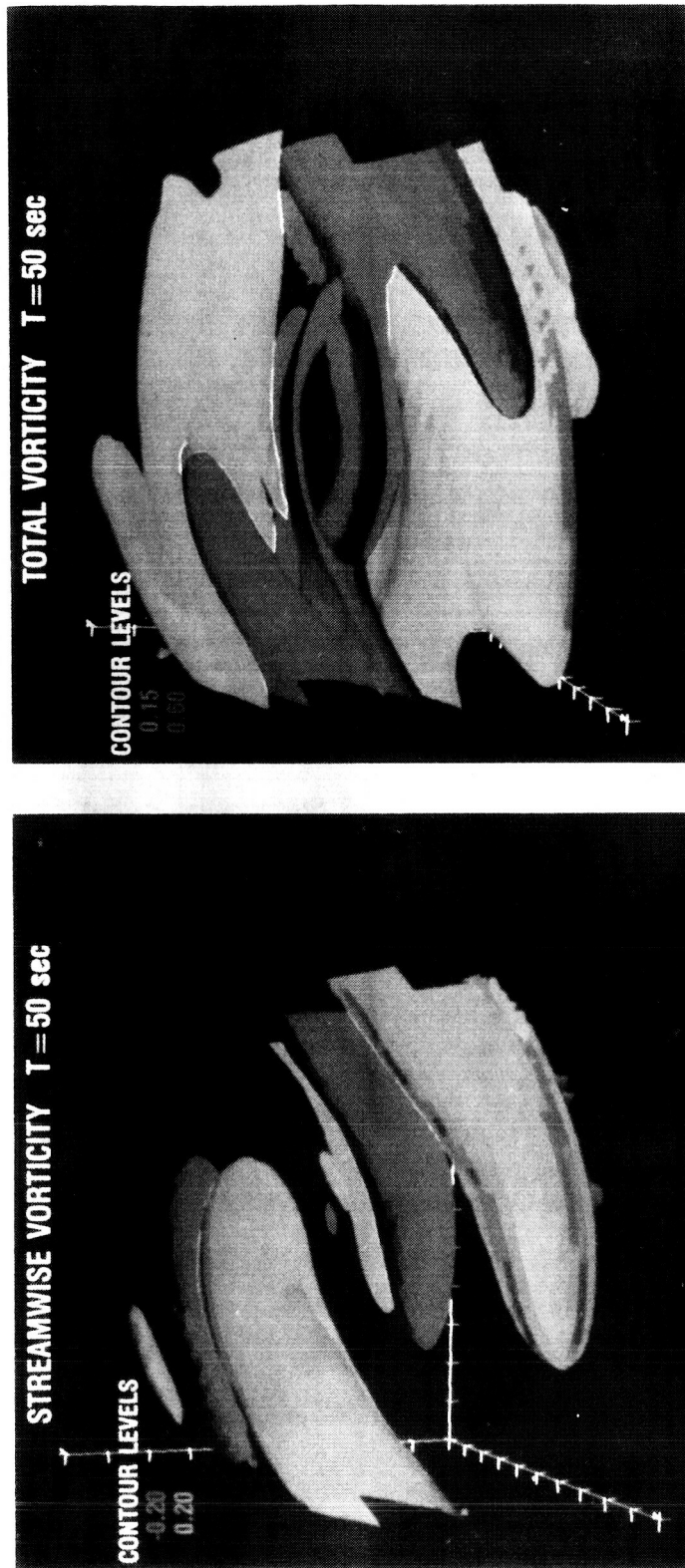


FIGURE 6. - THREE-DIMENSIONAL SURFACE PLOTS OF CONSTANT (STREAMWISE OR TOTAL) VORTICITY FOR A HARMONICALLY EXCITED MIXING LAYER NUMERICALLY SIMULATED USING 128x129x32 GRID POINTS.

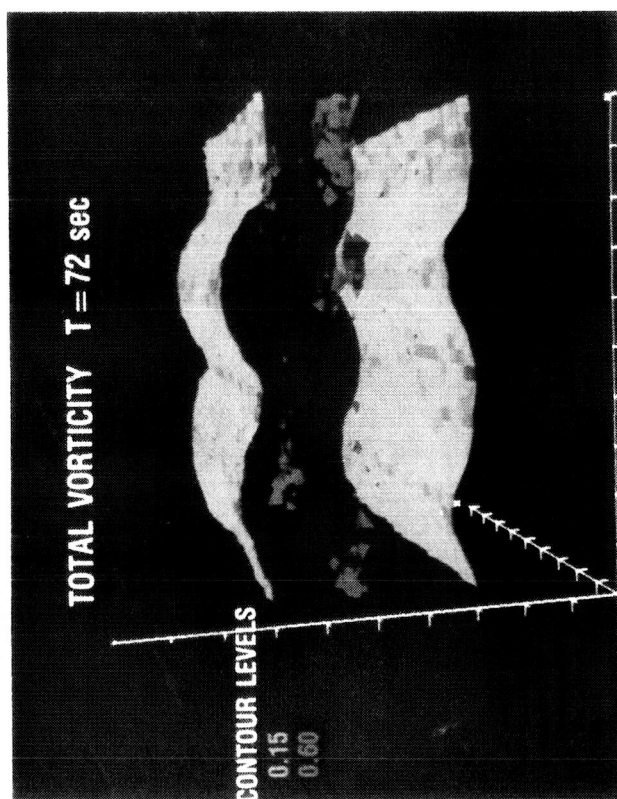
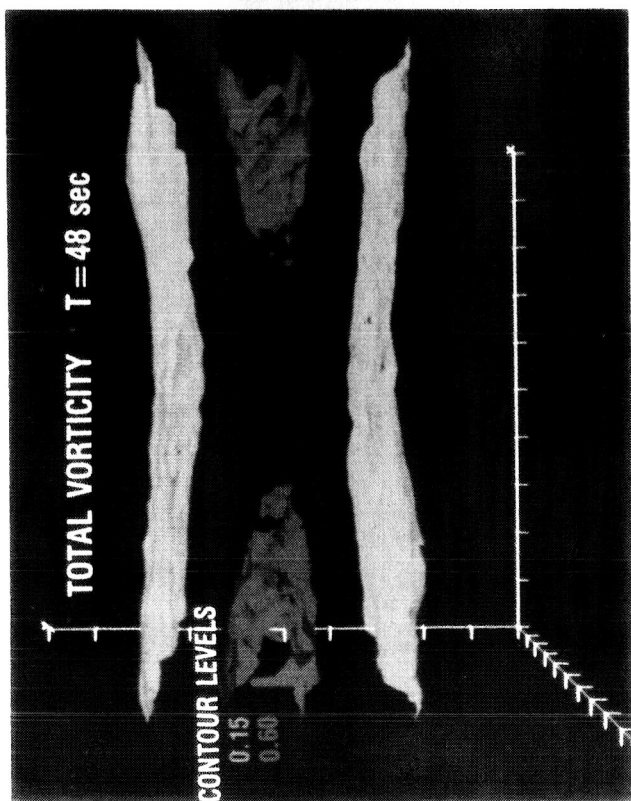
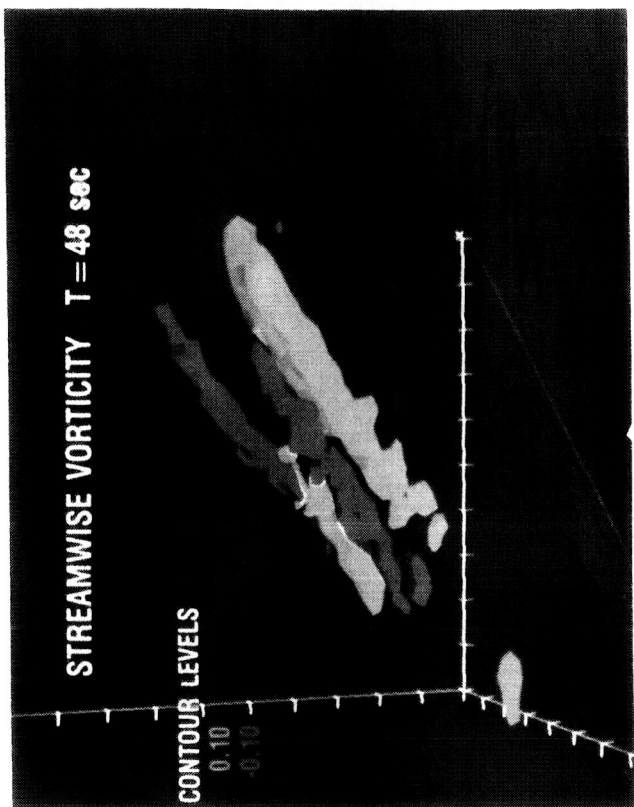
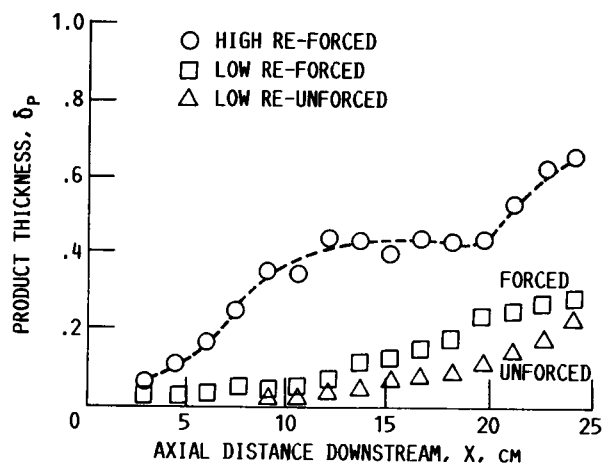
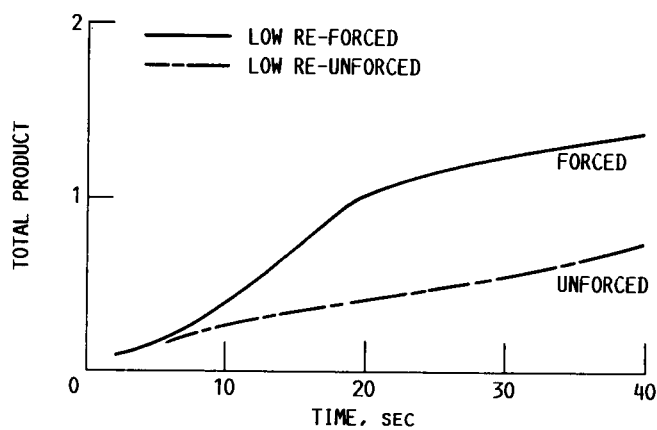


FIGURE 7. - THREE-DIMENSIONAL SURFACE PLOTS OF CONSTANT (STREAMWISE OR TOTAL) VORTICITY FOR A SHEAR LAYER PERTURBED WITH RANDOM NOISE IN THE INITIAL CONDITIONS. $32 \times 33 \times 32$ GRID POINTS USED IN THE X, Y, AND Z DIRECTION, RESPECTIVELY.



(A) EXPERIMENTAL DATA FROM REFERENCE 13.



(B) NUMERICAL SIMULATION RESULTS.

FIGURE 8. - EXPERIMENTAL AND NUMERICALLY SIMULATED PRODUCT LEVELS IN A PASSIVE CHEMICAL REACTION.

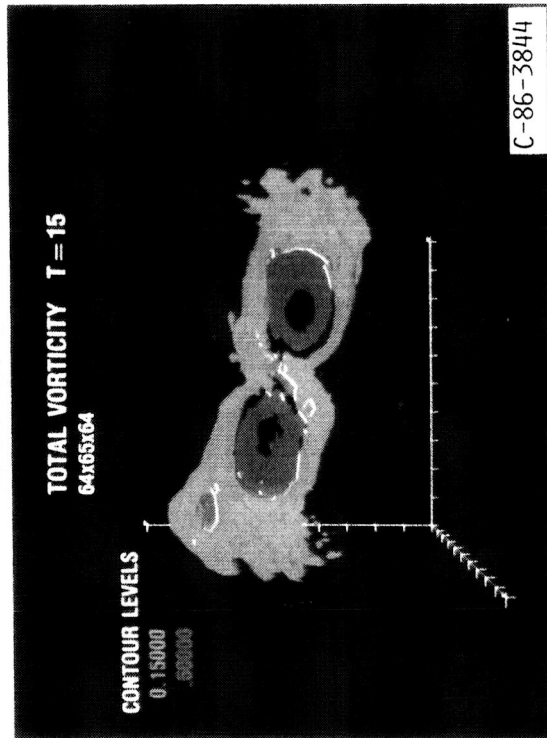
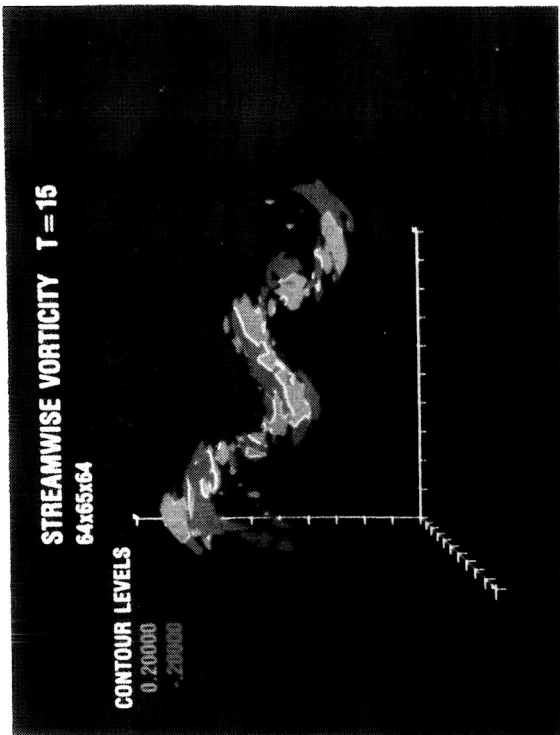
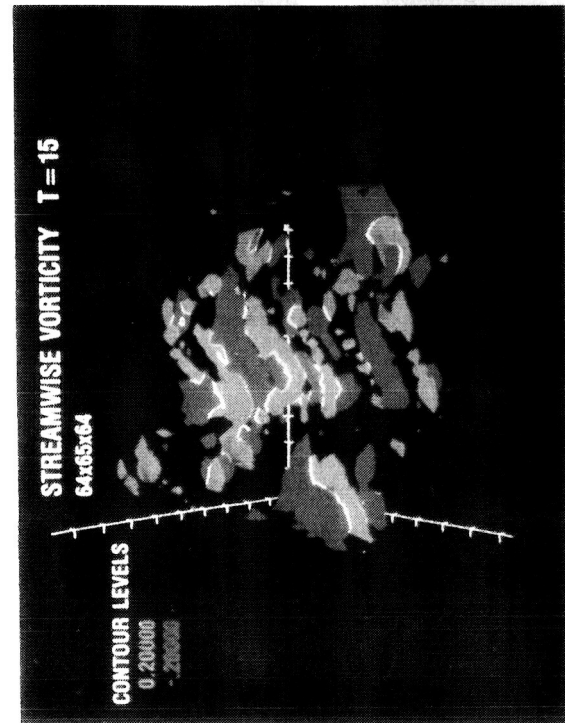


FIGURE 9. - THREE-DIMENSIONAL SURFACE PLOTS OF CONSTANT (STREAMWISE OR TOTAL) VORTICITY FOR SHEAR LAYER SUBJECT TO COMBINED HARMONIC AND SUBHARMONIC FORCING AT TIME OF 15 SECONDS. 64x65x64 GRID POINTS ARE USED IN THE X, Y, AND Z DIRECTION, RESPECTIVELY.

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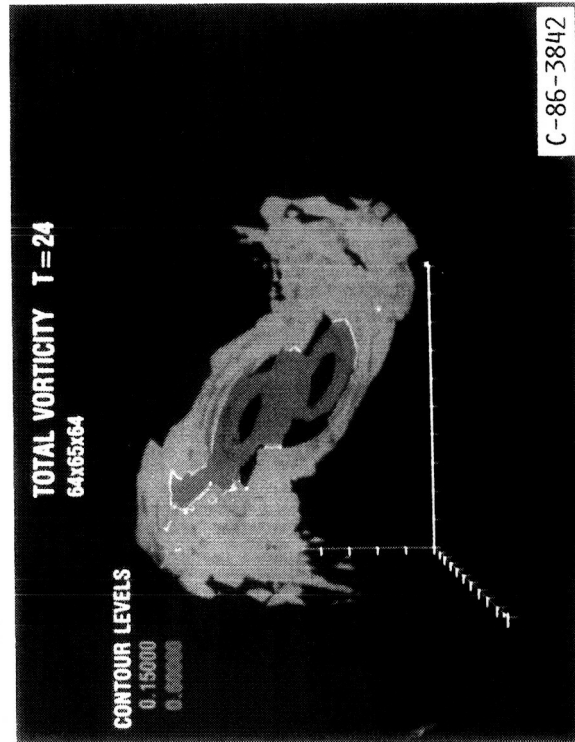
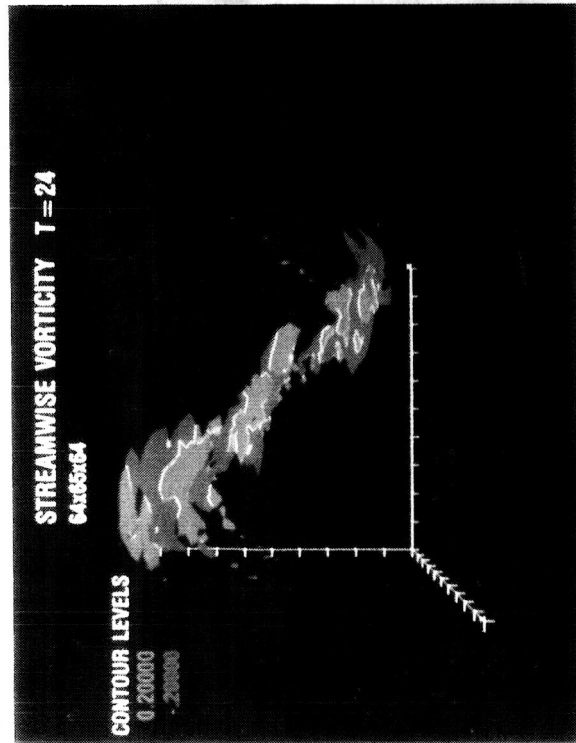
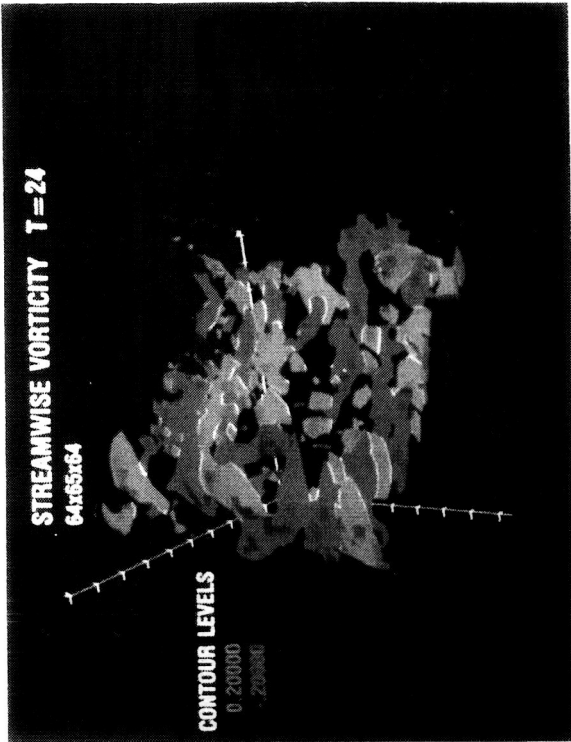


FIGURE 10. - THREE-DIMENSIONAL SURFACE PLOTS OF CONSTANT (STREAMWISE OR TOTAL) VORTICITY FOR SHEAR LAYER SUBJECT TO COMBINED HARMONIC AND SUBHARMONIC FORCING AT TIME OF 24 SECONDS. 64X65X64 GRID POINTS ARE USED IN THE X, Y, AND Z DIRECTION, RESPECTIVELY.

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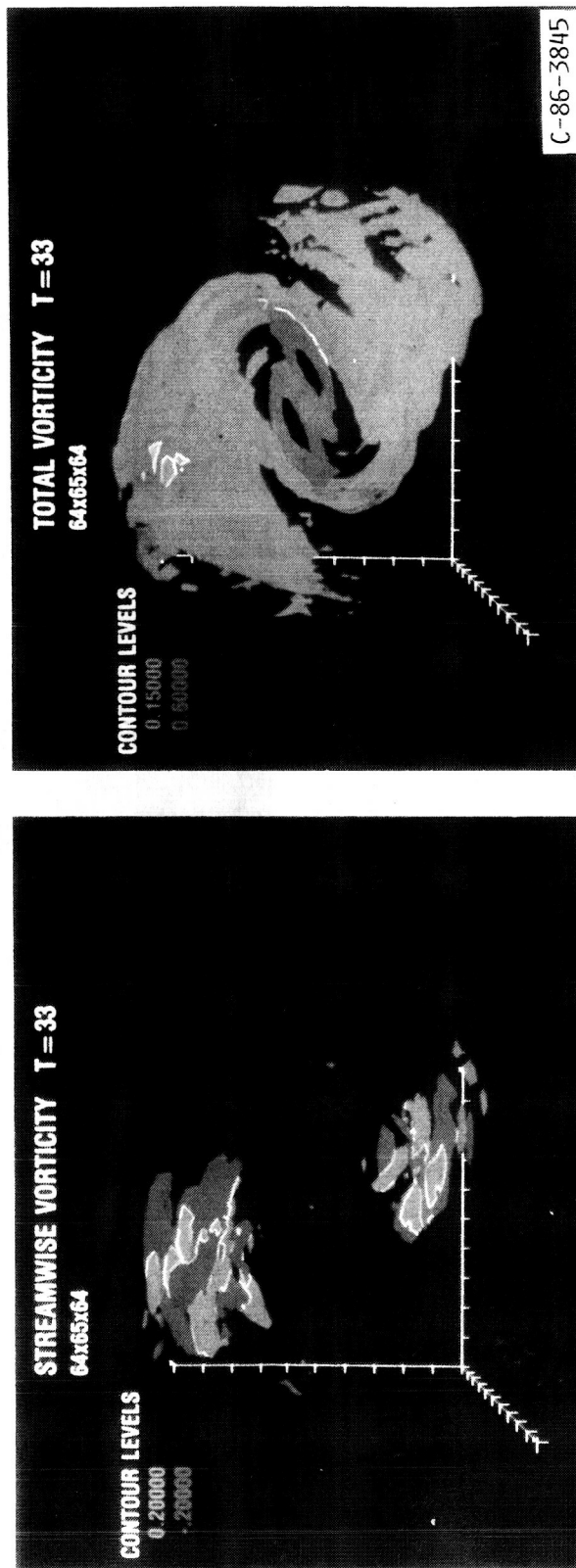


FIGURE 11. - THREE-DIMENSIONAL SURFACE PLOTS OF CONSTANT (STREAMWISE OR TOTAL) VORTICITY FOR SHEAR LAYER SUBJECT TO COMBINED HARMONIC AND SUBHARMONIC FORCING AT TIME OF 33 SECONDS. 64x65x64 GRID POINTS ARE USED IN THE X, Y, AND Z DIRECTION, RESPECTIVELY.

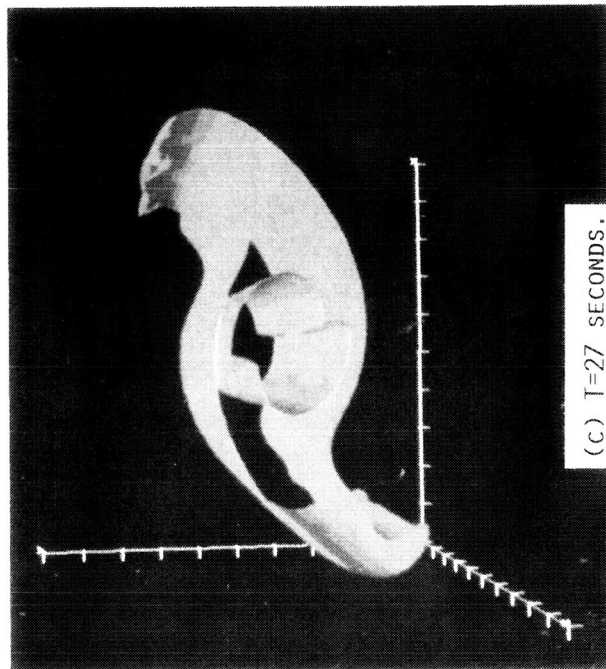
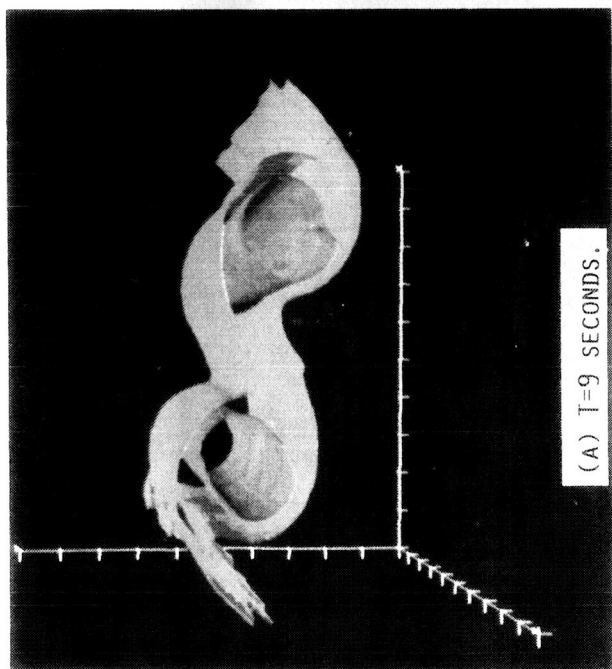
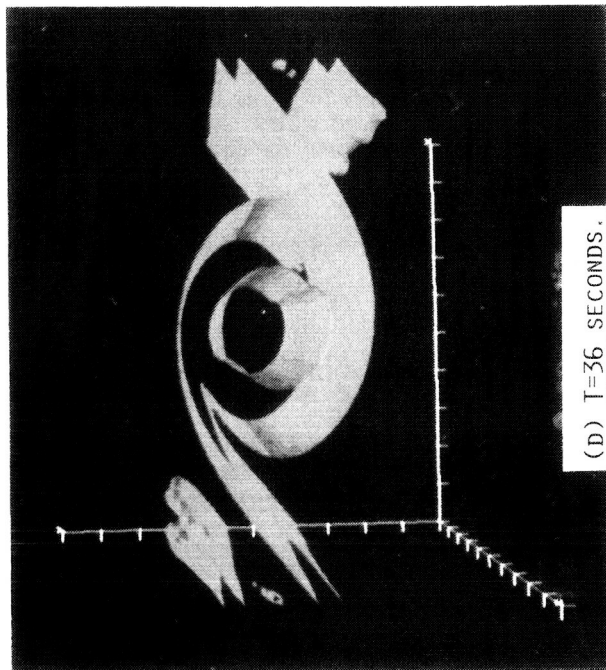
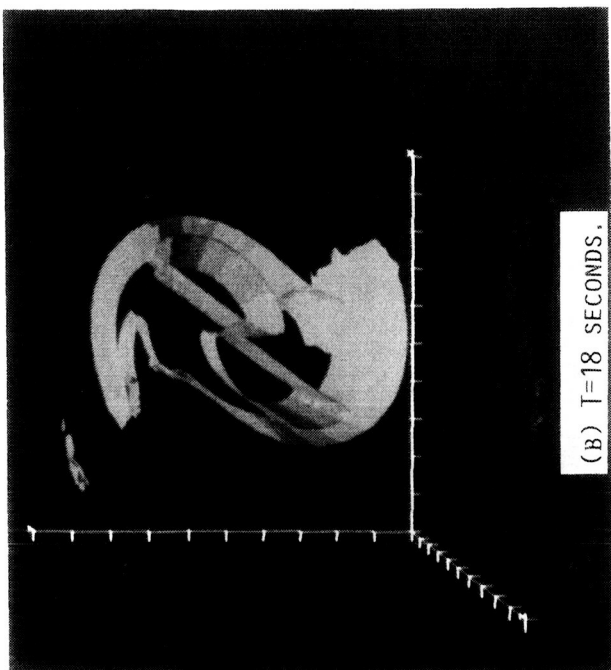


FIGURE 12. - THREE-DIMENSIONAL SURFACE PLOTS OF CONSTANT TOTAL VORTICITY AT TIMES OF 9, 18, 27, AND 36 SECONDS FOR SHEAR LAYER SUBJECT TO COMBINED HARMONIC AND SUBHARMONIC FORCING WITH VERY LOW LEVEL OF RANDOM NOISE IN THE INITIAL CONDITIONS. $128 \times 129 \times 32$ GRID POINTS ARE USED IN THE X, Y, AND Z DIRECTION, RESPECTIVELY. CYAN = 0.15 AND MAGENTA = 0.50.

1. Report No. NASA TM-88896		2. Government Accession No.		3. Recipient's Catalog No.	
4. Title and Subtitle Direct Numerical Simulations of a Temporally Evolving Mixing Layer Subject to Forcing				5. Report Date February 1987	
				6. Performing Organization Code 505-62	
7. Author(s) Russell W. Claus				8. Performing Organization Report No. E-3313	
				10. Work Unit No.	
9. Performing Organization Name and Address National Aeronautics and Space Administration Lewis Research Center Cleveland, Ohio 44135				11. Contract or Grant No.	
				13. Type of Report and Period Covered Technical Memorandum	
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, D.C. 20546				14. Sponsoring Agency Code	
15. Supplementary Notes Prepared for the 10th Symposium on Turbulence, cosponsored by the Office of Naval Research and the University of Missouri - Rolla, Rolla, Missouri, September 22-24, 1986.					
16. Abstract The vortical evolution of mixing layers subject to various types of forcing is numerically simulated using psuedospectral methods. The effect of harmonic forcing and random noise in the initial conditions is examined with some results compared to experimental data. Spanwise forcing is found to enhance streamwise vorticity in a nonlinear process leading to a slow, secondary growth of the shear layer. The effect of forcing on a chemical reaction is favorably compared with experimental data at low Reynolds numbers. Combining harmonic and subharmonic forcing is shown to both augment and later destroy streamwise vorticity.					
17. Key Words (Suggested by Author(s)) Numerical simulations Mixing layer			18. Distribution Statement Unclassified - unlimited STAR Category 34		
19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified		21. No. of pages 21	22. Price* A02	